Rotation Angle and Task Demands Influence Encoding of Ordinal Stimuli in the Ordinal Stimuli's Location Activated Context

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ABSTRACT

Although previous studies have investigated how ordinal stimuli are encoded in contexts that vary in locational congruency, conclusions regarding the encoding mechanism are inconsistent. The present study utilized Chinese Heavenly Stem characters, which are an ordinal sequence used to record astronomical phenomena in ancient China and are still frequently used to date, as stimuli to investigate the influence of rotation angle and task demands on the encoding of ordinal stimuli in contexts that varied in locational congruency. We randomly presented six of these characters at varying rotation angles (0° or 180°) on the left or right side of the screen. Participants were then instructed to classify the stimulus order (Experiment 1), location (Experiment 2) and color (Experiment 3) in a bimanual classification task. The results were as follows: (a) When participants classified stimuli according to order, both the ordinal position effect and the Simon effect were detected for unrotated stimuli. However, only the ordinal position effect was detected for rotated stimuli. (b) When participants classified stimuli according to spatial location, we observed only the spatial stimulus–response compatibility effect. (c) When participants classified stimuli according to color, we observed the Simon effect in all trials. However, the ordinal position effect was detected only in location-congruent trials. These results suggest that encoding of ordinal stimuli in contexts that varied in locational congruency was moderated by the processing difficulty of the stimuli and the task demands.

KEYWORDS

SNARC effect
Simon effect
ordinal position effect
mental rotation

INTRODUCTION

Numbers and ordinal stimuli are very useful in daily life, transmitting information across individuals and generations. Mental encoding of numerical and ordinal stimuli can also systematically influence the behavior of cognitive agents (Dehaene et al., 1990; Dehaene et al., 1993; Fischer et al., 2004; Gevers et al., 2003; Gevers et al., 2004; Wang et al., 2019). For example, the spatial–numerical association of response codes (SNARC) effect (or the ordinal position effect) has been described. In this effect, low numbers or ordinal stimuli (e.g., 1, 2, 3 or "A," "B," "C") elicit a faster left-hand response on a bimanual classification task and high numbers or ordinal stimuli (e.g., 7, 8, 9 or "E," "F," "G") elicit a faster right-hand response (Dehaene et al., 1990; Dehaene et al., 1993; Previtali et al., 2010; Prpic et al., 2016; van Dijck & Fias, 2011; Zhang et al., 2016; Wang et al., 2021b).

Why does processing numerical and ordinal stimuli systematically influence individual behavior? Originally, some studies assumed that the SNARC effect (or the ordinal position effect) was generated from the spatial representation of numbers and ordinal stimuli in long-term memory and thus depended on individual reading and writing experience (Dehaene et al., 1993; Shaki et al., 2009). Alternatively, these effects were thought to stem from genetic factors (Bulf et al., 2016; Bulf et al., 2022; de Hevia et al., 2014; McCrink & de Hevia, 2018). However, in recent years, an increasing number of studies have linked the SNARC effect (or the ordinal position effect) to the spatialization of numbers (and ordinal stimuli) in working memory. In this framework, cognitive agents select appropriate encoding cues based on their experience or the demands of the task to spatially encode numbers and ordinal stimuli online (Abrahamse et al., 2014; Abrahamse et al., 2016; van Dijck & Fias, 2011).

Although the online spatial encoding of numerical and ordinal stimuli in working memory can explain most of the SNARC effect and the ordinal position effect, one basic question relevant to the encod-

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ing mechanism of numbers and ordinal stimuli is how they are encoded. When only one encoding cue is available in numbers or ordinal stimuli, individuals can only utilize that cue to spatially encode the stimuli. However, we often encounter numerical or ordinal stimuli that contain more than one encoding cue. When more than one encoding cue is present, the encoding of these stimuli is complex and flexible (Bächtold et al., 1998; Mingolo et al., 2021; van Dijck & Fias, 2011). For example, imagine a clock. On a clock, both the number magnitude (i.e., 12) and location (top) are present. Thus, number location substantially influences the spatial encoding of numerical magnitude (Bächtold et al., 1998). This finding implies that numerical magnitude is not an exclusive cue for spatial encoding in contexts where more than one encoding cue is available. However, only a few studies have examined this phenomenon, and the results do not indicate how the numbers and ordinal stimuli are spatially encoded online in working memory when more than one encoding cue is present. To understand the mechanism underlying the encoding of numbers and ordinal stimuli in contexts with more than one encoding cue, more research is needed.

Thus, the encoding of numbers and ordinal stimuli influence individual behavior. However, before the SNARC effect was identified, many studies found that encoding location also systematically influences behavioral responses (Fitts & Seeger, 1953; Müsseler et al., 2018; Simon & Small, 1969; Yamaguchi & Proctor, 2019). For example, when stimuli are randomly presented on the left or right side of the screen and the participants are instructed to report the location of the stimuli by pressing an assigned key, stimuli presented on the left side induced a faster key-pressing response from the left hand, and stimuli presented on the right side induced a faster key-pressing response from the right hand. This well-known phenomenon is called the spatial stimulus–response compatibility effect (Fitts & Seeger, 1953; Müsseler et al., 2018). This finding can also be extended to classifications based on nonspatial stimuli characteristics (e.g., color) and is known as the Simon effect (Simon & Small, 1969; Yamaguchi & Proctor, 2019). The Simon effect is caused by encoding the stimuli location and response information together (Hommel, 1993; Proctor & Cho, 2006; Proctor & Xiong, 2015). Notably, the SNARC effect substantially differs from the Simon effect; the former reflects the congruency between the implicit representation of numerical or ordinal stimuli in space and the response side, whereas the latter reflects the congruency between the explicit presentation location of stimuli and the response side. In addition, these effects exert differing influences on response latency. Specifically, the magnitude of the SNARC effect (or the ordinal position effect) increases with increases in response latency (Didino et al., 2019; Gevers et al., 2006). However, the magnitude of the Simon effect decreases and even disappears with increases in response latency. Increases in response latency can often be induced by increasing stimulus complexity and task difficulty (Hommel, 1994; Proctor et al., 2011; Zorzi & Umiltá, 1995).

From the Simon effect, one can reasonably speculate that number location provides a new spatial cue other than the numerical magnitude cue for encoding numbers. Thus, the encoding mechanism of stimuli based on spatial and order encoding cues may effectively be explored in contexts with multiple encoding cues present. Two recent studies investigated how people encode ordinal stimuli and how this encoding changes when the location of the ordinal stimuli is manipulated in the Simon task (Shi et al., 2020; Wang et al., 2021a). Unfortunately, these studies reached inconsistent conclusions. Specifically, Shi et al. (2020) utilized days of the week as ordinal stimuli. They presented day stimuli on left or right screens and then had participants perform a bimanual classification task depending on day order. They found that the ordinal position effect and Simon effect were mutually exclusive in the ordinal classification task. However, Wang et al. (2021a) utilized letters as stimuli, which were easier for participants to recognize, and employed the same paradigm and tasks to investigate how the locations of ordinal stimuli influence encoding and individual responses. They found that the ordinal position effect and the Simon effect were not mutually exclusive in a letter order classification task. Therefore, how people encode ordinal stimuli in contexts that vary in locational congruency remains unclear and needs further research.

Researching this question would provide more insight than merely characterizing the mechanism underlying the encoding of ordinal stimuli. In the field of human factors engineering, individuals often encounter tasks that must be completed by pressing specified keys marked with ordinal stimuli (e.g., entering a specific password consisting of a series of letters and numbers to log into their personal accounts). Therefore, researching how the encoding of ordinal stimuli influences individuals' responses in contexts that vary in locational congruency would also inform the design of an optimal human-machine interface for entering ordinal stimuli, thus improving the efficiency of high-demand tasks and the positive experience of users.

In theory, both ordinal cues and spatial cues can be used to spatially encode ordinal stimuli. The spatial encoding of stimuli may vary according to stimulus complexity and task difficulty. Specifically, the influence of spatial cues on stimulus encoding may be greater for simpler stimuli and easier tasks (Hommel, 1994; Proctor et al., 2011; Zorzi & Umiltá, 1995). Therefore, we speculated that in contexts where the location and ordinal information of stimuli are both available as encoding cues, only the ordinal cue will be used to encode ordinal stimuli when they are difficult to process. In contrast, we expected that both the spatial cue and ordinal cue may be used to encode ordinal stimuli when they are easy to process. In other words, how people encode ordinal stimuli may be moderated by the difficulty of processing ordinal stimuli in contexts where both location and ordinal information of stimuli are available as encoding cues. In the present study, we designed serial experiments to test these hypotheses.

The processing difficulty of ordinal stimuli depends on stimulus complexity and task demands. For example, identifying the semantic information of ordinal stimuli is more challenging and takes longer than identifying their color (Didino et al., 2019). Several studies on mental rotation have found that when presented with rotated stimuli, individuals can rotate these stimuli to the standard orientation and recognize them by comparing them with their mental representations of known stimuli. Rotated stimuli are therefore more difficult to recognize than nonrotated stimuli, with the processing difficulty peaking at a rotation angle of 180° (Cooper, 1975; Shepard & Metzler, 1971; Yang &

Lupker, 2019; Wang et al., 2020). Thus, mental rotation is a very effective tool for manipulating the complexity of ordinal stimuli.

Although previous studies have frequently employed letters, days, and months as ordinal stimuli, when these stimuli are rotated 180°, participants are probably able to recognize some of them by obvious features (e.g., the letter E faces right in the standard orientation and faces left, Ǝ, when rotated 180°; individuals can thus recognize it according to the direction it faces). Alternatively, rotations of some stimuli may be concealed because of their symmetry (e.g., "Monday" in Chinese is "一"; the two forms, unrotated and rotated 180° are very similar). Therefore, it is very difficult to manipulate ordinal stimulus complexity through mental rotation tasks when using common stimuli. The Chinese Heavenly Stem characters 甲 (jia), 乙 (yi), 丙 (bing), 丁 (ding), 戊 (wu), 己 (ji), 庚 (geng), and so forth, are ordinal, similar to letters, and were used to observe astronomical phenomena in ancient China. Moreover, Chinese people still frequently encounter these characters in their daily lives. These stimuli have no obvious features when they are rotated but are not symmetric, allowing their rotation to be easily perceived. These features make these stimuli more useful for manipulating the complexity of ordinal stimuli than the commonly used stimuli.

In addition, task demands are a key factor that influences which encoding cue is preferentially attended to during the spatial encoding of numbers and ordinal stimuli. For example, when attending to the semantic information of numerical and ordinal stimuli, the magnitude and order of these stimuli were easily activated and selected to encode stimuli (Abrahamse et al., 2016; Shi et al., 2020; Wang et al., 2021a). Moreover, the response latency, driven by task demands, may also moderate the selection and use of encoding cues (Didino et al., 2019; Gevers et al., 2006; Hommel, 1994). Therefore, the present study used mental rotation to manipulate the complexity of ordinal stimuli and administered various tasks in which the participants were directed to attend to different encoding cues to systematically investigate the spatial encoding of ordinal stimuli and how ordinal information interacts with context.

Specifically, we rotated the Heavenly Stem characters 甲 (jia), 乙 (yi), 丙 (bing), 戊 (wu), 己 (ji), and 庚 (geng) 0° or 180° and presented those ordinal stimuli on left or right screens to participants. Participants were then asked to indicate whether the presented characters appeared before or after the character 丁 (ding) in the order of Heavenly Stem characters (Experiment 1), which side of the screen the characters were presented on (Experiment 2), or whether the characters were black or red (Experiment 3). In these three experiments, we systematically investigated how people encode stimuli based on spatial location and ordinal information to elucidate the mechanism underlying the spatial encoding of ordinal stimuli.

EXPERIMENT 1

This experiment investigated how the rotation angle of ordinal stimuli influences encoding. We predicted that the ordinal position effect and Simon effect would co-occur while processing unrotated Heavenly Stem characters but that only the ordinal position effect would be found while processing Heavenly Stem characters rotated 180°.

Methods

PARTICIPANTS

G*Power 3.1 was used to estimate the minimum sample size needed for this experiment. We set the effect size f to 0.25, α (probability of type I errors) to 0.05, and power (1-β; probability of type II errors) to 0.8. The results showed that at least 16 participants were required for a 2 × 2 × 2 within-participant design. As all three experiments utilized this design, the same minimum sample size applied for all experiments, and the calculations were not repeated. Thirty-two university students (28 females; M_{age} = 20.63, SD = 1.1 years; range = 18 to 23 years) volunteered to participate in this experiment. All the participants were right-handed and had normal or corrected-to-normal vision. The research protocol was approved by the Medical Ethics Committee of Huzhou University, and written informed consent was provided by all participants. These latter points (protocol approval and collection of informed consent) were followed for all three experiments in this study.

2.1.2 Stimuli and Apparatus Six Heavenly Stem characters 甲 (jia), 乙 (yi), 丙 (bing), 戊 (wu), 己 (ji), and 庚 (geng) were used as ordinal stimuli. Each Heavenly Stem character was either not rotated (0° rotation) or rotated 180° (see Figure 1). A laptop computer with a 14 in., screen was used to present the stimuli. The visual angle of the probe stimuli was 4.26°, and the viewing distance was 47 cm.

DESIGN

A 2 × 2 × 2 (ordinal congruency [order-congruent vs. order-incongruent] × rotation angle [0° vs. 180°] × locational congruency [location-congruent vs. location-incongruent]) within-subject design was used in this experiment. Response times (RTs) were used as the dependent variable. In the order-congruent trials, the participants indicated Heavenly Stem characters that preceded 丁 (ding) by pressing the left key and indicated the Heavenly Stem characters that followed 丁 (ding) by pressing the right key. In the order-incongruent trials, the participants indicated the Heavenly Stem characters that preceded 丁 (ding) by pressing the right key and indicated the Heavenly Stem characters that followed 丁 (ding) by pressing the left key. In the location-congruent trials, the participants were asked to press the left key in response to stimuli presented on the left side of the screen and to press the right key in response to stimuli presented on the right side of the screen. In

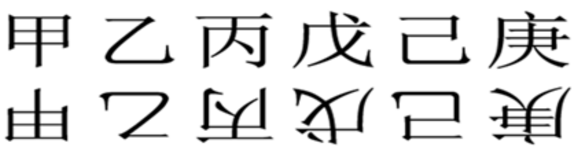

FIGURE 1.
The Heavenly Stem characters used in the present study ("jia", "yi", "bing", "wu", "ji", and "geng"). These stimuli are ordinal, similar to letters of the alphabet. In ancient China, Heavenly Stem characters were used to record astronomical phenomena. At present, these characters are still frequently used in daily life. Stimuli are not rotated in the first line and are rotated 180° in the second line.

the location-incongruent trials, the participants were asked to press the right key in response to stimuli presented on the left side of the screen and to press the left key in response to stimuli presented on the right side of the screen. The definitions of ordinal congruency and locational congruency in the next two experiments were the same as those in Experiment 1.

PROCEDURE

The experiment was administered in E-prime 1.1 software. The procedure for a single trial was as follows. First, a central fixation cross was presented on the screen. After 500 ms, the fixation cross disappeared, and then the Heavenly Stem characters were randomly presented on the left or right side of the screen for 3,000 ms. When stimuli were presented, the participant was instructed to make a correct decision as quickly as possible by pressing the specified key. Once the participants responded to the probe stimuli (or failed to respond within 3 s), the probe stimuli disappeared and were replaced by a blank screen, which lasted for 1,500 ms (see Figure 2).

All trials in the present experiment were evenly divided into two blocks under the opposite response model. In one block, the participants pressed a left key (the "F" key) to indicate the Heavenly Stem characters that preceded 丁 (ding) and pressed a right key (the "J" key) to indicate the Heavenly Stem characters that followed 丁 (ding). The response key associations were reversed in the other block. The order of these two blocks was counterbalanced between participants. Each Heavenly Stem character was repeated three times each, in the left location and in the right location, in each block, for a total of 144 trials in this experiment. Each block contained 72 trials. Before each block, participants completed 12 practice trials to familiarize themselves with the experimental requirements. The experiment took approximately 20 minutes total.

Results and Discussion

We excluded the RTs of incorrect responses as well as those more than three *SD*s from the mean for each treatment (5.92%) before analyzing the data. A repeated-measures analysis of variance (ANOVA) indicated a significant main effect of ordinal congruency, $F(1, 31) = 5.19$, $p < .05$, $\eta^2 = 0.143$, specifically, RTs in order-congruent trials (637±10.28 ms) were shorter than RTs in order-incongruent trials (657±13.85 ms). This indicates the presence of the ordinal position effect in the classification of the Heavenly Stem character order (see Figure 3).

A significant main effect of rotation angle was also found, $F(1, 31) = 8.53$, $p < .01$, $\eta^2 = 0.216$, specifically, participant RTs in trials with stimuli rotated 0° (641±11.54 ms) were shorter than those in trials with stimuli rotated 180 ° (653±11.58 ms). This finding indicates that the processing of rotated Heavenly Stem characters was more difficult than that of unrotated Heavenly Stem characters, confirming that processing difficulty was effectively manipulated by mental rotation. The interaction between locational congruency and rotation angle was significant, $F(1, 31) = 12.40$, $p = .001$, $\eta^2 = 0.286$, indicating that the rotation angle of stimuli influenced the Simon effect while processing the location of stimuli in this experiment. Further simple effect analysis found that RTs in the location-congruent trials (632±12.81 ms) were faster than those in the location-incongruent trials (649±10.86 ms) when viewing unrotated stimuli, $F(1, 31) = 9.37$, $p < .01$, $\eta^2 = 0.232$. This finding indicates that the Simon effect was present. However, the differences in the RTs between the location-congruent and location-incongruent trials were not significant when viewing stimuli rotated 180°, $F(1, 31) = 1.23$, $p = .28$, $\eta^2 = 0.038$. This finding indicates that the Simon effect was absent (see Figure 4). No other significant main effects or interactions were captured in this experiment, *ps* > .15.

This experiment manipulated processing difficulty by rotating the stimuli and then investigated how stimuli were encoded based on spatial and ordinal information in contexts where participants attended to the ordinal information. The results indicated the ordinal position effect was present while processing both the unrotated and rotated stimuli. However, only the Simon effect was present while processing unrotated stimuli. These results suggest that the processing difficulty of ordinal stimuli moderates encoding in contexts in which both spatial and ordinal information are available.

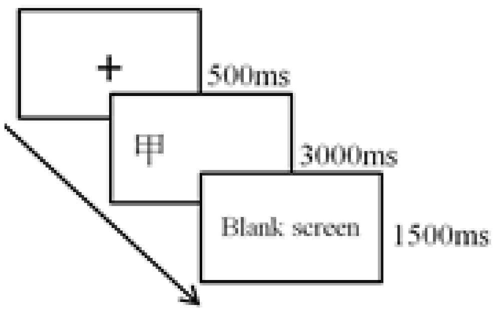

FIGURE 2.

An example trial from Experiment 1. All stimuli, including the Heavenly Stem characters rotated 0° and 180° were randomly presented to the participants after the fixation cross disappeared.

EXPERIMENT 2

This experiment used a location classification task to investigate how attending to spatial cues over ordinal cues in contexts where both cues are present influenced encoding in addition to the rotation angle of ordinal stimuli. We predicted that the spatial stimulus–response compatibility effect would be present but that the ordinal position effect would be absent in this experiment.

Methods

PARTICIPANTS

Thirty-six university students (30 females; $M_{age} = 20.61$, $SD = 1.1$ years; range = 18 to 23 years) volunteered to participate in this experiment. All the participants were right-handed and had normal or corrected-to-normal vision.

STIMULI AND APPARATUS

The stimuli and apparatus used in Experiment 2 were similar to those in Experiment 1.

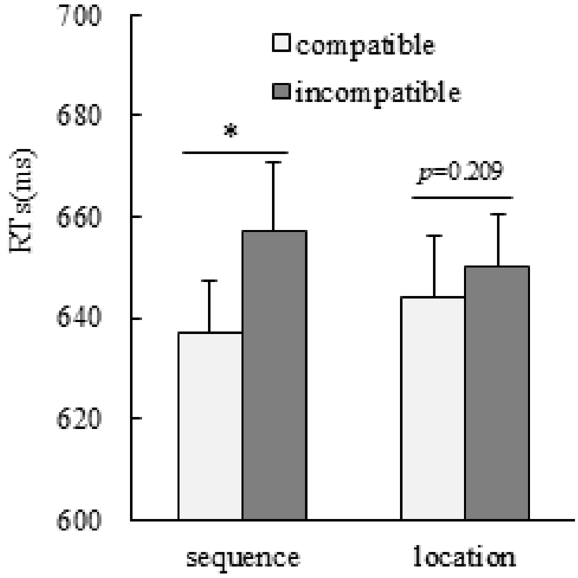

FIGURE 3.

RTs of the participants for both order- and location-congruent trials and order- and location-incongruent trials in the ordinal classification task involving the Heavenly Stem characters. The error bars in this figure and those below indicate the standard error.

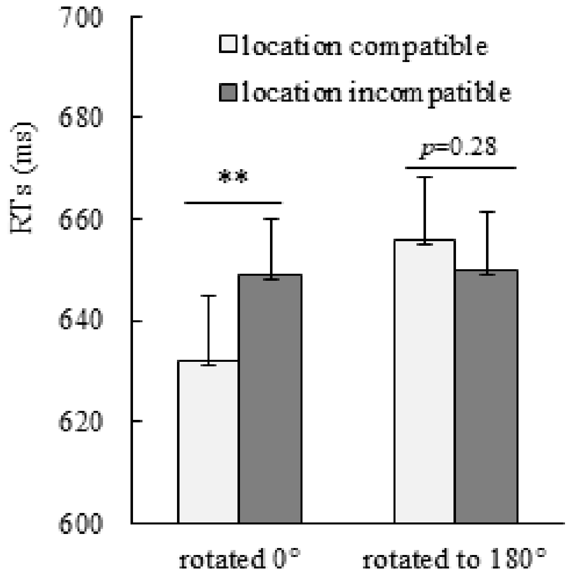

FIGURE 4.

RTs of the participants for unrotated and rotated stimuli in location-congruent and location-incongruent trials.

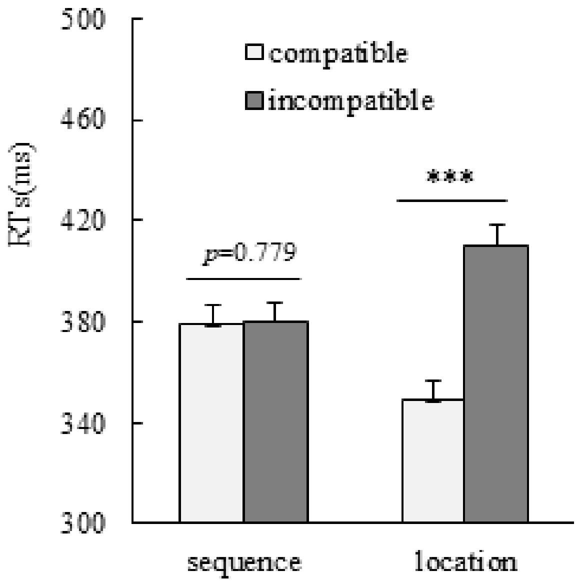

FIGURE 5.

RTs of the participants for both order- and location-congruent trials and order- and location-incongruent trials in the location classification task with the Heavenly Stem characters.

DESIGN

A 2 × 2 × 2 (ordinal congruency [order-congruent vs. order-incongruent] × rotation angle [0° vs. 180°] × 2 locational congruency [location-congruent vs. location-incongruent]) within-subjects design was used in this experiment. RTs were the dependent variable. The definitions of ordinal congruency and locational congruency were the same as those in Experiment 1.

PROCEDURE

The procedure of Experiment 2 was similar to that of Experiment 1, except that a location classification task was administered in Experiment 2, in which the participants were asked to indicate whether the stimuli were presented on the left or right side of the screen by pressing the left or right key.

Results and Discussion

We excluded the RTs of incorrect responses as well as RTs more than three *SD*s from the mean for each treatment (3.22%) before analysis. A repeated-measures ANOVA found that only the main effect of locational congruency was significant, $F(1, 35) = 124.55$, $p < .001$, $\eta^2 = 0.781$, meaning that the location-congruent trials (349±7.96 ms) had faster RTs than the location-incongruent trials (410±8.55 ms). This indicates the presence of the spatial stimulus–response compatibility effect. No other main effects or interactions were significant in this experiment, $ps > .257$, implying that the ordinal position effect was absent in this experiment (see Figure 5).

This experiment aimed to investigate how rotation angles influenced the encoding of stimuli when participants attended to the spatial cues in contexts where both spatial and ordinal cues were available. The results showed that only the spatial stimulus–response compatibility effect was present, which indicates that the participants encoded the ordinal stimuli based only on spatial cues and that the moderation of processing difficulty on the encoding of ordinal stimuli disappeared when the spatial location of stimuli was emphasized.

EXPERIMENT 3

This experiment administered a color classification task to further investigate how the rotation angle of the ordinal stimuli moderates stimuli encoding in contexts where spatial and ordinal cues are available but not emphasized. As the color of stimuli can be identified regardless of rotation angle, we predicted that the influence of the rotation angle on the Simon effect would be decreased or absent. In other words, we predicted that the Simon effect would be present while processing both unrotated and rotated stimuli in this experiment, whereas the ordinal position effect would depend on the processing of the stimuli's ordinal information.

Methods

PARTICIPANTS

Thirty-six university students (28 females; M_{age} = 20.48, SD = 1.18 years of age; range = 18 to 23 years) volunteered to participate in this experiment. All the participants were right-handed and had normal or corrected-to-normal vision.

STIMULI AND APPARATUS

The apparatus used in Experiment 3 was similar to that used in Experiment 1. The stimuli were also similar to those in Experiment 1, with the exception that all stimuli were presented in red or black.

DESIGN

A 2 × 2 × 2 (ordinal congruency [order-congruent vs. order-incongruent] × rotation angle [0° vs. 180°] × locational congruency [location-congruent vs. location-incongruent]) within-subjects design was used in this experiment. RTs were the dependent variable.

PROCEDURE

The procedure of Experiment 3 was similar to that of Experiment 1, except that we administered a color classification task in which participants were instructed to indicate whether the stimuli were black or red by pressing the left or right key. In addition, each Heavenly Stem character was presented twice in each color, rotation angle, and location in each block, such that this experiment contained 192 formal trials.

Results and Discussion

We excluded the RTs of incorrect responses as well as RTs more than three SDs from the mean for each treatment (5.99%) before analysis. A repeated-measures ANOVA indicated a significant main effect of locational congruency, $F(1, 31) = 11.04$, $p < .01$, $\eta^2 = 0.263$, meaning that RTs in location-congruent trials (488±10.41 ms) were shorter than RTs in location-incongruent trials (501±9.68 ms). This finding indicates that the Simon effect was present (see Figure 6).

We also found a significant main effect of the rotation angle, $F(1, 31) = 13.25$, $p = .001$, $\eta^2 = 0.299$, such that RTs in unrotated trials (489±9.40 ms) were shorter than those in rotated trials (500±10.31 ms). This finding indicates that participants automatically processed the sematic information of the stimuli in the color classification task. A significant interaction between locational congruency and ordinal congruency was also found, $F(1, 31) = 5.23$, $p < .05$, $\eta^2 = 0.144$, which indicates that the ordinal position effect was influenced by the Simon effect. Therefore, we further analyzed the ordinal position effect in the location-congruent and location-incongruent conditions. A simple effects analysis showed that RTs in order-congruent trials (484±10.11 ms) were shorter than RTs in order-incongruent trials in the location-congruent condition (492±11.06 ms), $F(1, 31) = 5.23$, $p < .05$, $\eta^2 = 0.144$, indicating that the

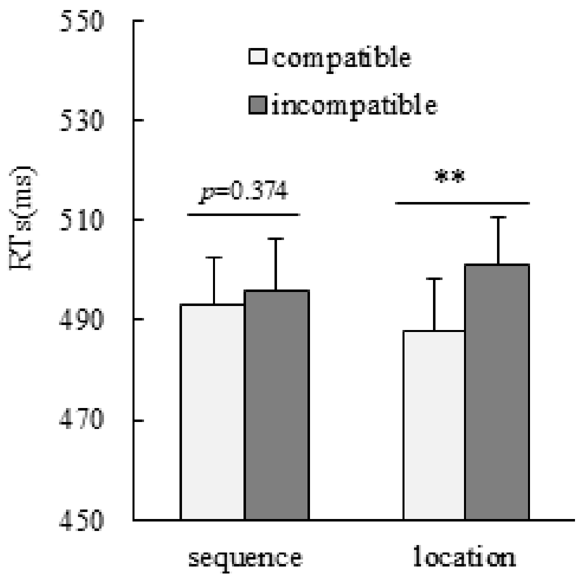

FIGURE 6.

RTs of the participants for both order- and location-congruent trials and order- and location-incongruent trials in the color classification task with Heavenly Stem characters.

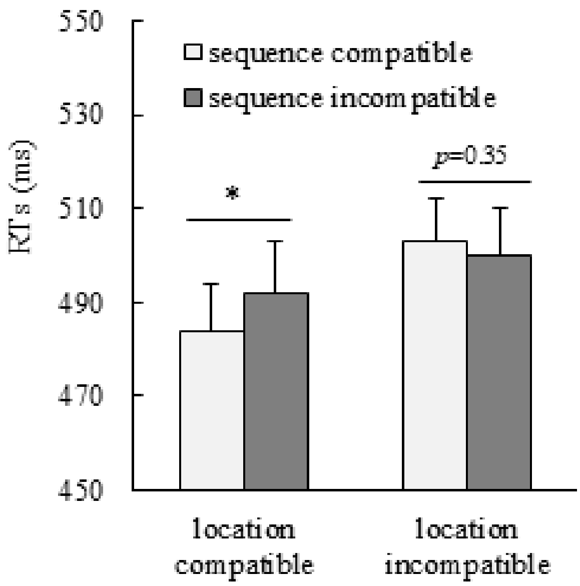

FIGURE 7.

RTs of the participants in order-congruent and order-incongruent trials in the location-congruent and location-incongruent conditions.

ordinal position effect was present. However, in the location-incongruent condition, the RTs in order-congruent trials (503±9.15 ms) did not differ from those in order-incongruent trials (500±10.31 ms), $F(1, 31) = 0.35$, $p = .56$, $\eta^2 = 0.011$, indicating that the ordinal position effect was absent (see Figure 7). No other significant main effects or interaction effects were found in this experiment, *ps* > .20.

To further quantitatively analyze differences in the ordinal position effect and Simon effect among all three experiments, we first calculated the magnitude of the ordinal position effect by subtracting RTs in order-congruent trials from those in order-incongruent trials. We also calculated the magnitude of the Simon effect by subtracting RTs in location-congruent trials from those in location-incongruent trials. Both calculations followed the methods of previous studies (Shi et al., 2020; Wang et al., 2021a; Wang et al., 2022). Then, we compared the RTs and the magnitude of the ordinal position effect and the Simon effect among all three trials with a one-way ANOVA. The results showed that the RTs on the ordinal classification task (647±11.35 ms) were significantly longer than those on the color classification task (495±9.75 ms), which were significantly longer than those on the location classification task (379±7.79 ms). The magnitude of the ordinal position effect in the ordinal classification task (20.36±8.94 ms) was significantly larger than that in the location classification task (0.56±1.97 ms) and the color classification task (3.08±19.28 ms). Additionally, the magnitude of the Simon effect in the location classification task (61.44±5.51 ms) was significantly larger than that in the ordinal classification task (5.62±4.38 ms) and the color classification task (13.42±4.04 ms). To investigate the influence of response latency on the ordinal position effect and Simon effect, we conducted a Pearson correlation analysis and linear regression analysis. We found that the relationship between response latency and the ordinal position effect was significant, $r(100) = .37$, $p < .01$ and that the RTs positively predicted the magnitude of the ordinal position effect, $B = 0.10$, $SE = 0.03$, $t = 3.88$, $p < .001$; in other words, the magnitude of the ordinal position effect increased with increasing RTs. The relationship between response latency and the Simon effect was also significant, $r(100) = -.59$, $p < .01$, and the RTs negatively predicted the magnitude of the Simon effect, $B = -0.18$, $SE = 0.02$, $t = -7.29$, $p < .001$. In other words, the magnitude of the Simon effect decreased with increasing RTs.

This experiment investigated whether the rotation angle of ordinal stimuli moderates encoding when neither the spatial nor ordinal information is emphasized. The results indicated the Simon effect was present in all trials but that the ordinal position effect was only present in location-congruent trials. Moreover, the rotation angle did not interact with either the ordinal position effect or the Simon effect and did not influence the interaction between the ordinal position effect and the Simon effect, which indicates that processing difficulty did not moderate stimuli encoding in this experimental condition.

GENERAL DISCUSSION

Although previous studies have investigated the mechanism underlying the encoding of ordinal stimuli across experimental contexts, it remains unclear how people encode stimuli in contexts where both spatial and ordinal information is present. A key factor is that previous studies did not effectively manipulate the processing difficulty of ordinal stimuli. Therefore, the present study utilized the Heavenly Stem characters, for the first time, as ordinal stimuli and manipulated processing difficulty with mental rotation to investigate the encoding mechanism in various tasks.

In Experiment 1, we randomly presented unrotated Heavenly Stem characters and characters rotated 180° on the left or right side of the screen and asked the participants to perform a bimanual classification task based on the ordinal information of the stimuli. We found that the ordinal position effect was present across all trials, but the Simon effect was present only in the processing of unrotated Heavenly Stem characters. This finding indicates that the participants encoded stimuli based on ordinal information when this information was emphasized. In addition, when participants' implicit representation of the ordinal stimuli was consistent with the response side, the explicit spatial information also played a substantial role in the encoding of ordinal stimuli. In contrast, when the implicit representation of the ordinal stimuli was inconsistent with the response side, participants encoded stimuli based only on their ordinal information in the ordinal classification task. Previous studies on the Simon effect have indicated that the Simon effect decreases and even disappears with increasing stimulus complexity (Hommel, 1994; Proctor et al., 2011; Zorzi & Umiltá, 1995). Experiment 1 found that the Simon effect was present while processing unrotated stimuli but absent while processing rotated stimuli. This result indicates that the spatial information mainly influenced encoding by shortening the RT and further verified the processing mechanism of the Simon effect.

Interestingly, the ordinal position effect was not influenced by the rotation angle as it was present while processing both unrotated and rotated ordinal stimuli. A comparison of the ordinal position effect and the Simon effect while processing unrotated and rotated ordinal stimuli indicates that the influence of processing difficulty on the encoding of spatial information was larger and more sensitive than that on the encoding of ordinal information. Previous studies have found that the magnitude of the Simon effect decreased but that the magnitude of the SNARC effect increased or remained constant with increases in response latency (Didino et al., 2019; Gevers et al., 2006; Mapelli et al., 2003). The sharp difference between the Simon effect and the ordinal position effect found in Experiment 1 further replicated the results of these previous studies and verified that the time scale of the Simon effect and the ordinal position effect differs.

Shi et al. (2020) utilized days as ordinal stimuli to investigate the encoding mechanism in an ordinal classification task in contexts where both ordinal and spatial information are available. They found that the participants encoded stimuli based only on their ordinal information. Wang et al. (2021a) utilized letters, which are easier to process, instead of days and further investigated the encoding mechanism in an ordinal classification task in contexts when spatial information was indirectly presented. They reported the simultaneous influence of the Simon effect and the ordinal position effect. Although days and letters differ, they are both ordinal stimuli. The main difference is that of processing difficulty. Therefore, according to the above two studies, we speculated that processing difficulty might moderate how people encode stimuli in contexts where both spatial and ordinal information is available (Shi et al., 2020; Wang et al., 2021a). One flaw in this line of reasoning is that the difference between these two studies may reflect stimulus-specific effects, which they could not rule out. In the present study, we manipulated the processing difficulty of stimuli in Experiment 1 by rotating ordinal stimuli at different angles. This manipulation effectively rules out the effects of stimulus specificity by precisely manipulating the processing difficulty of ordinal stimuli. The results of Experiment 1 illustrate that the processing difficulty of ordinal stimuli moderates encoding in contexts where both spatial and ordinal information are available while performing an ordinal classification task.

In Experiment 2, we further investigated how the rotation angle of ordinal stimuli influences encoding in contexts where both spatial and ordinal information is available but participants are instructed to attend to the spatial information. We found only the spatial stimulus–response compatibility effect on the location classification task for both the unrotated and rotated ordinal stimuli. In addition, the rotation angle did not influence the spatial stimulus–response compatibility effect. Thus, when preferentially attending to spatial information, the participants encoded ordinal stimuli based only on the spatial information, and the processing difficulty did not moderate how the participants encoded ordinal stimuli in the location classification task. Indeed, the results of Experiment 2 were consistent with those of Shi et al. (2020) and Wang et al. (2021a), who found that only the spatial stimulus–response compatibility effect was present when the spatial information of ordinal stimuli was emphasized by the location classification task. Considering the results of the above two studies (Shi et al., 2020; Wang et al., 2021a) and the results of Experiment 2, it appears that when the spatial information of ordinal stimuli was directly emphasized, the participants encoded ordinal stimuli based only on spatial information.

In addition, we also found no significant effect of the rotation angle in Experiment 2. This result implies that the participants did not process the semantic information of stimuli in the location classification task. The explanation is simple: In location classification tasks, participants can effectively and quickly identify which location the ordinal stimuli were presented and do not need to rotate the stimuli to the standard orientation regardless of rotation angle. Therefore, the rotation angle did not moderate the encoding of ordinal stimuli in this context. This explanation also indicates why only the spatial stimulus–response compatibility effect was present for both days with relatively high processing difficulty (Shi, et al., 2020) and letters with relatively low processing difficulty (Wang et al., 2021a) during a location classification task with ordinal stimuli. Moreover, the first two experiments in our study showed that both spatial and ordinal information of stimuli may be simultaneously encoded in trials when focusing on the ordinal information of ordinal stimuli but that only the spatial information was encoded when participants attended to the spatial information of ordinal stimuli. Therefore, the influence of ordinal and spatial information on the encoding of ordinal stimuli is different and asymmetric.

In Experiment 3, we further instructed participants to attend to the color of ordinal stimuli, a characteristic not related to either spatial or ordinal cues, and investigated how these stimuli were encoded in contexts where both spatial and ordinal information was available. First, we found a significant main effect of rotation angle; specifically, unrotated stimuli elicited significantly shorter RTs than rotated stimuli. This finding suggests that the participants automatically processed the semantic information of ordinal stimuli in the color classification task and is consistent with the Stroop effect, which predicts that participants automatically process the semantic information of stimuli despite attending to stimulus color (Besner et al., 1997; Cohen, 1990; Hasshim & Parris, 2021).

Importantly, in Experiment 3, the Simon effect was present in all conditions. Experiment 1 indicated that the Simon effect was moderated by the processing difficulty of ordinal stimuli, driven by rotation angle. However, Experiment 3 indicated that the Simon effect was present in all conditions, regardless of rotation angle. This difference may be due to a floor effect in Experiment 3, in which the RTs for all ordinal stimuli were shorter in the color classification task (approximately 500 ms) than in the ordinal classification task (approximately 645 ms), so the Simon effect was observed even while processing rotated ordinal stimuli in the color classification task.

Another interesting finding from Experiment 3 is that the ordinal position effect was present in the location-congruent trials but not in the location-incongruent trials. Shi et al. (2020) and Wang et al. (2021a) also investigated the relationship between the Simon effect and the ordinal position effect in a color classification task with ordinal stimuli. However, they found that only the Simon effect was present. Based on their findings, Shi et al. (2020) and Wang et al. (2021a) claimed that the participants encoded only the spatial information of ordinal stimuli in the color classification task. In other words, they concluded that the ordinal information of stimuli did not play a substantial role in encoding in the color classification task. However, we found that both the Simon effect and the ordinal position effect were present in the location-congruent trials in Experiment 3. The Simon effect was always present when processing ordinal stimuli, indicating that the spatial information of ordinal stimuli played a key role in encoding during the color classification task. This finding is consistent with that of previous studies (Shi et al., 2020; Wang et al., 2021a). Our findings differed from previous studies in that the ordinal position effect was present in the location-congruent trials, indicating that the ordinal information of stimuli also played a substantial role in encoding ordinal stimuli during location-congruent trials in the color classification task. The substantial role of the ordinal cues on the color classification task in the location-congruent trials not only enhances our understanding of the interaction between the ordinal and spatial information of ordinal stimuli but also further confirmed that the influence of ordinal and spatial cues on ordinal stimuli encoding are different and asymmetric.

A comparison of the ordinal position effect among the three experiments in the present study also revealed that the magnitude of the ordinal position effect was large in Experiment 1 (long RTs), zero in Experiment 2 (shortest RTs) and small in Experiment 3 (medium RTs). In addition, the RTs to ordinal stimuli were positively related to and predicted the magnitude of the ordinal position effect. Several previous studies have indicated that a stronger SNARC effect is strongly and positively related to a slower RT (Didino et al., 2019; Mitchell et al., 2012). The difference among the present three experiments in the magnitude of the ordinal position effect and the positive relationship between RTs and the ordinal position effect further verify the positive relationship between a stronger SNARC effect and a slower RT. Since location and color decisions are generally very quick, the SNARC effect and ordinal position effect are not always detected (or are difficult to replicate) in tasks involving the location and color classification of numbers and ordinal stimuli. However, in Experiment 3, the ordinal position effect was surprisingly detected in the color classification task with ordinal stimuli in the location-congruent trials. Although the RTs on the color classification task were shorter, and the RTs in the location-congruent trials were shorter than those in the location-incongruent trials, the ordinal position effect was detected in the shorter response latency on location-congruent trials compared to the location-incongruent trials. Obviously, this result is inconsistent with the prediction that a stronger SNARC effect is strongly and positively related to a slower RT. This finding implies that the SNARC effect may also be present in color classification tasks and that RT is not the only factor that influences the SNARC effect. This implication is also supported by some previous studies, in which the authors detected the SNARC effect and the ordinal position effect on a color classification task with numbers or ordinal stimuli (Fumarola et al., 2014; Wang et al., 2019).

Several studies related to the Stroop effect found that participants also automatically processed the semantic information of stimuli even on the color classification task (Besner et al., 1997; Cohen, 1990; Hasshim & Parris, 2021). Depending on the mental number line, automatic processing of the semantic information of numerical or ordinal stimuli in turn might elicit the SNARC effect and the ordinal position effect on color classification tasks (Dehaene et al., 1993). Given the significant ordinal position effect detected on location-congruent trials and the main effect of rotation angle, the semantic information of ordinal stimuli was automatically processed by participants. Although the semantic information of ordinal stimuli was automatically processed, the ordinal position effect was not detected in the location-incongruent trials, implying that the processing of the semantic information of ordinal stimuli was not the only factor that elicited the ordinal position effect. There may be an intermediate stage between the spatial representation of numbers and ordinal stimuli and the detection of the SNARC effect and the ordinal position effect.

Synthesizing all these findings, we deduce that the influence of spatial location on the encoding of ordinal stimuli was relatively stable and that the substantial influence of spatial location on encoding only influenced short RTs. However, the role of ordinal information on encoding is very complex. It was not only moderated by the task demands and response latency but also the spatial information of ordinal stimuli. Thus, the encoding of ordinal stimuli in contexts where spatial and ordinal information were both available was moderated by the processing difficulty of the ordinal stimuli and the task demands. In addition, it was influenced by the impact of spatial information on ordinal cues. After the SNARC effect (or the ordinal position effect) was detected in the processing of numbers and ordinal stimuli, many researchers further examined its mechanism. At first, they assumed that the spatial representation of numbers and ordinal stimuli along the mental number line was due to long-term memory. As research progressed, scientists found that the SNARC effect (or the ordinal position effect) was very flexible and could not be explained by the spatial representation of numbers and ordinal stimuli in long-term memory. Several researchers proposed or evaluated a working memory theory, which states that cognitive agents can construct numbers or ordinal stimuli online according to appropriate cues (including the implicit representation of numbers and ordinal stimuli on a mental number line) in working memory, to explain this effect. The SNARC effect (or the ordinal position effect) is indirectly elicited by the spatial representation of numbers or ordinal stimuli in working memory (Abrahamse, et al., 2014; Abrahamse, et al., 2016; van Dijck & Fias, 2011). Under the working memory perspective, there may be an intermediate stage between the spatial representation of numbers and ordinal stimuli in long-term memory and the detection of the SNARC effect and the ordinal position effect. This deduction was verified by the present study. Thus, the results of the present study support the working memory explanation of the SNARC effect (or the ordinal position effect).

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DATA AVAILABILITY

The data of this manuscript can downloaded from http://dx.doi.org/10.17632/hdph7r6rs8.2

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